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Abstract

Despite the importance of balance in Acrobatic Gymnastic Pyramid performance, there is limited biomechanical analysis of balance during this activity. The aims of this study were to analyse the effect of pyramid difficulty on the centre of pressure (COP) excursion and its inter-trial variability, and determine which parameters had strongest relationship with performance. Forty-seven acrobatic gymnasts performed five trials of back and front pyramids and a third more difficult, handstand pyramid on a force platform. Pyramids were held for 7 seconds and surface area, range, mediolateral amplitude and anteroposterior amplitude of the CoP were examined to analyse balance. The pyramid scores were obtained from qualified judges to assess the performance. Results showed higher CoP excursions and inter-trial variability during the execution of the high difficulty pyramid. Higher judges' scores were associated with lower CoP excursions in all the pyramids regardless of the difficulty. Similarly, correlation between inter-trial variability and pyramid performance were observed, although these coefficients were lower than those reported for the relationship between CoP excursion and performance. These results suggested that CoP monitoring could help coaches and gymnasts to assess the pyramid instability more accurately.

Keywords: balance; CoP; dyadic performance; score; static position

Introduction

The ability to balance is a prerequisite to execute many sports techniques, therefore understanding the relationship between balance and performance is of interest to scientists, coaches and athletes (Hrysomallis, 2011). This ability is even more important for those sports and physical activities where maintaining a static position is a requirement, such as dance (Steinberg, Waddington, Adams, Karin, & Tirosh, 2018); shooting sports (Ko, Han, & Newell, 2018; Negahban, Aryan, Mazaheri, Norasteh, & Sanjari, 2013); or gymnastic sports (Shigaki et al., 2013; Floría, Gómez-Landero, & Harrison, 2015; Opala-Berdzik et al., 2018). Moreover, in the gymnastics disciplines, a judge scores these static positions (e.g. handstand, balances on the foot) as part of the final score for the exercise. The importance of these static positions on performance depends on the gymnastic discipline. In acrobatic gymnastics, a large proportion of the final score is based on correct execution of balance formation or pyramids (Federation Internationale de Gymnastique, 2017). A pyramid is a characteristic formation composed of at least one gymnast in the base supporting partner(s) on the top while maintaining a static balance for a minimum of three seconds (Federation Internationale de Gymnastique, 2017). In competition, the acrobatic gymnasts perform three types of exercise: balance, dynamic and combined. Balance and combined exercises involve collaboration between gymnasts to perform various static pyramids, usually with different levels of difficulty, as an important part of their competitive routines. Technical faults such as movement amplitude, non-optimal body shape, hesitations, instability or falls penalise the score of each pyramid. In addition, greater difficulty in the pyramids increases the final score (Federation Internationale de Gymnastique, 2017).

One of the biomechanical variables most often used to assess balance is the centre of pressure (CoP) excursion. Previous studies suggest that to achieve a competent execution of the gymnastic element (e.g. handstand), the CoP excursion needs to be minimised (Kochanowicz et al., 2018; Omorczyk et al., 2018). The CoP has been recorded during the execution of individual gymnastic skills such as the handstand (Blenkinsop, Pain, & Hiley, 2016; Kochanowicz et al., 2018; Omorczyk et al., 2018; Rohleder & Vogt, 2018; Sobera, Siedlecka, Piestrak, Sojka-Krawiec & Graczykowska, 2007) or one leg toe stance (Sobera et al., 2007); and in static formations carried out by two people as pyramids, although this has received limited attention in the literature (Floría et al., 2015). Despite the importance of the static maintenance of the pyramid in acrobatic gymnastics, only one study has examined the maintenance of balance in pyramid performance (Floría et al., 2015). The authors found associations between the CoP path length and the judges scores during the execution of simple initiation pyramids. Given the relevance of the difficulty level on performance in acrobatic gymnastics, it is important to determine the relationship between CoP excursion and judges scores in pyramids of varying difficulty. In general, higher displacements of the CoP have been observed with increasing difficulty of balance tasks (Lubetzky, Price, Ciol, Kelly, & McCoy, 2015; Caballero, Barbado, Davids, & Moreno, 2016), therefore, it may be expected that CoP displacements increase in pyramids of greater difficulty.

To master pyramids it is common for gymnasts to repeat the element several times during the same session to develop adaptability of performance and the ability to perform successfully despite unexpected events. Pyramids vary in levels of difficulty, where there is a continuous coupling between partners to maintain the pyramid balance. Therefore, some movement variability can be expected and the extent of this may provide important information on the adaptability to continuously changing conditions. Recent studies report on intra-individual variation in movement patterns as an integral characteristic of any motor task allowing flexible adaptations to improve movement performance (Davids, Glazier, Araújo, & Bartlett, 2003; Preatoni et al., 2013; Baida, Gore, Franklyn-Miller, & Moran, 2018).

Previous studies have analysed the relationship between movement variability and sports performance, although the conclusions are not unanimous. Some studies have related lower movement variability with higher performance during the execution of a diverse range of motor tasks such as the volleyball spike (Serrien, Goossens, & Baeyens, 2018), various types of punches (Lenetsky, Brughelli, Nates, Cross, & Lormier, 2018) or a specific shooting task (Ko et al., 2018). By contrast, other studies have found associations between higher performance and higher movement variability in motor tasks such as, high bar giant circles (Busquets, Marina, Davids, & Angulo-Barroso, 2016; Hiley, Zuevsky, & Yeadon, 2013) or table tennis forehand (Iino, Yoshioka, & Fukashiro, 2017). The conflicting findings could be due to the analysis approach used and/or type of movement variability analysed, since movement variability can be classified as variability in the patterns of movement (coordination) or variability in the task outcome (Glazier, Wheat, Pease, & Bartlett, 2006). Depending on the type of variability analysed, a skilled motor performance could be characterised by low variability in outcome measures, and exhibit high variability in movement patterns (Bradshaw, Maulder, & Keogh, 2007; Wilson, Simpson, Van Emmerik, & Hamill, 2008; Ko et al., 2018). The CoP excursion might be considered an outcome parameter derived from the movement patterns performed by the gymnasts to maintain the pyramid balance. It would be expected that a higher performance in the pyramid execution would be accompanied by a low inter-trial variability in the measures that describe the CoP excursion, however, this should be confirmed in future studies.

Given the importance of balance for the correct execution of a pyramid, it is necessary to understand how the CoP excursion and its associated inter-trial variability relate to pyramid performance. Thus, the objectives of this study were (1) to analyse the effect of the degree of difficulty of the pyramids on the CoP excursion (outcome measures) and its variability between trials, and (2) to determine the relationship between the CoP outcome measures and its inter-trial variability with the pyramid score, ascertaining which of the outcome measures or inter-trial variability had more influence on scores. It was hypothesised that (1) the CoP excursion should increase in response to increased task difficulty, and (2) the higher score in the pyramid would be associated by a low inter-trial variability in the CoP excursion.

Methods

Participants

Forty-seven acrobatic gymnasts (consisting 34 females and 13 males) were recruited for this study. All participants had competed at national championship level in official categories. Participants were grouped in twenty-five different pairs (n = 25). Each pair was formed by two gymnasts with different roles: Base (22) and top gymnasts (25). Three base gymnasts formed two different pairs each, grouped with different top gymnasts. The base gymnasts were aged 17 ± 3 years (mean ± SD), with a mass of 62 ± 12 kg and a height of 1.64 ± 0.10 m. The top gymnasts were aged 11 ± 2 years, with a mass of 33 ± 6 kg and a height of 1.39 ± 0.08 m. All participants were free from any musculoskeletal injury that may have interfered with their ability to perform pyramids. The study had ethical approval from the Pablo de Olavide University Research Ethics Committee. All adult participants and parents/guardians of children participants signed informed consent forms before participating in the study.

Testing protocol

Each pair was instructed to perform three different pyramids, 'stand back on bent elbows' (Back, Figure 1a), 'stand front on bent elbows' (Front, Figure 1b), 'handstand on bent elbows' (Handstand, Figure 1c) on the regular surface of a single force platform (AMTI AccuPower, Watertown, MA, USA) maintaining the position for 7 s. These pyramids were selected because they are basic positions in Acrobatic Gymnastics and they have differing levels of difficulty (Federation Internationale de Gymnastique, 2016). The back and front pyramids were categorised as low difficulty (difficulty value = 2 points, according to the Code of Points; Federation Internationale de Gymnastique, 2016). In these pyramids, the top is supported on the feet at two points by the hands of the base, including also the support on the collarbones of the base in the back pyramid. The handstand pyramid was categorised as high difficulty (difficulty value = 3 points, according to the Code of Points; Federation Internationale de

Gymnastique, 2016). In it, the top gymnast executes a handstand position supported exclusively by the hands of the base. In all cases, the base gymnast stands and supports the top gymnast with bent elbows, while the top gymnast tries to keep the body in full extension.

[Figure 1]

Before data collection, the participants carried out their usual general warm-up, as well as the specific warm ups for the execution of pyramids on mats under the supervision of their coach. Since all subjects regularly performed these kinds of pyramids in their daily training, only a brief five-minute practice was needed to ensure the participants could complete the tasks comfortably and without risk in a satisfactory level before executing the pyramids on the force platform.

During the performance of the pyramids, the base gymnast stood with both feet on the platform to facilitate the recording of the CoP excursion at a frequency of 200 Hz. Five successful trials for each pyramid type were registered for each pair, with at least 2–3 min rest allowed between pyramids. The trials were presented in random order. Since in competition, each pair performed between 6 and 10 pyramids, a maximum of 10 trials were set for each pair in order to mitigate fatigue effects. Consequently, 13 pairs performed five for each Front and Handstand pyramids, and another 12 pairs performed five for each Back and Handstand pyramids.

Data analysis

Performance measures were defined and obtained as follows. Performance of each trial was judged live by three certified acrobatics judges with more than five years of experience, who determined the technical penalties of the pyramid performance. The final pyramid score was obtained as the mean of the three judges' scores. All trials were videotaped (Hero 4, GoPro Inc., San Mateo, California, USA) so the judges could review the score given in and revise in cases of doubt. All penalties were consistent with the Code of Points in Acrobatic Gymnastics

(Federation Internationale de Gymnastique, 2017), observing aspects related to movement amplitude, body shape, hesitations, instability and falls. The standard judging score was avoided since this is more suitable for assessing complete exercises than evaluating single elements (Floría et al., 2015; Miletic, Sekulic, & Wolf-Cvitak, 2004). Therefore, a tenth of a simple penalty was transformed into half a point penalty, and the final score was the sum of the deductions observed. The reliability of the judges score was tested by assessing the intraclass correlation coefficient (ICC= 0.950 with 95% confidence limits 0.938-0.960). ICC was calculated using a one-way random effects model with average measures, where judges were considered to represent a random selection of possible judges, who rated all gymnasts of the sample (Pajek, Cuk, Pajek, Kovac, & Leskošek, 2013).

Balance measures obtained to analyse the CoP outcomes and inter-trial variability were amplitude of displacement of the CoP, range trajectory and surface area of the CoP. The amplitude of CoP displacement in the mediolateral (Amplitude_Y) (1) and anteroposterior (Amplitude_X) (2) directions were calculated as:

$$\text{Amplitude}_Y = \max\{\text{CoP}_Y\} - \min\{\text{CoP}_Y\} \quad (1)$$

$$\text{Amplitude}_X = \max\{\text{CoP}_X\} - \min\{\text{CoP}_X\} \quad (2)$$

Where CoP_Y and CoP_X are the position of CoP in anteroposterior (x) and mediolateral (y) axis; and max and min are the single highest and lowest values recorded in a given trial. Both amplitudes were used to form a rectangle with a diagonal corresponding to the range of CoP:

$$\text{Range}_{\text{CoP}} = \sqrt{\text{Amplitude}_Y^2 + \text{Amplitude}_X^2} \quad (3)$$

The surface area (Area_{Cop}) (4) represents the area covered by the trajectory of the CoP within a 95% confidence interval ellipse area. This was estimated from the standard deviations of the CoP in the anteroposterior and mediolateral directions. Each standard deviation was multiplied by 1.96 to obtain the anteroposterior (x) and mediolateral (y) radii of the ellipse and, finally, the surface area was calculated as:

$\mathrm{Area}_{CoP} = \pi \cdot (1.96 \cdot SD\{CoP_Y\}) \cdot (1.96 \cdot SD\{CoP_X\})$ (4)

Statistical analyses

Statistical analyses were conducted using SPSS version 22.0 (IBM, Armonk, NY, USA). Non-parametric statistics were used based on: the research design of the study; the limited number of expert participants available; and the fact that deductions assigned by the judge were an ordinal variable (Preatoni et al., 2013). The median and median absolute deviation values (MAD) of the five successful trials were used for the statistical calculations. Medians and 95% confidence limits of each participant group were computed for all the measured variables. MAD was utilised for estimating the variability between trials (Preatoni et al., 2013). The Wilcoxon test was used to evaluate the differences between low and high difficulty pyramids. Significance level was set at $p < 0.05$. The effect size was used to evaluate the magnitude of differences using $r = Z/\sqrt{N}$ (Rosenthal,1994). The criteria to interpret the effect size were: small = 0.00–0.29; moderate = 0.30–0.49; large ≥ 0.50 (Cohen, 1977). Statistical analysis was completed by the estimation of the Spearman's rank order correlations to assess the degrees of association between judge scores and balance parameters, as well as between judge scores and inter-trial variability. Significance level was set at $p < 0.05$. Based on the recommendations of Hopkins (2006), the magnitude of the correlation coefficient was considered to be 0.0-0.09 trivial, 0.1-0.29 small, 0.3-0.49 moderate, 0.5-0.69 large, 0.7-0.89 very large, 0.9-0.99 nearly perfect.

Results

During the performance of the low difficulty pyramids, higher scores were achieved compared to those obtained in high difficulty pyramid ($Z \leq -2.93$, $P < 0.05$, effect size = -0.9, large) (Table 1). These significant differences in performance between pyramids were also observed in the parameters that described the CoP excursion ($Z = -2.93$, $P < 0.05$, effect size =-0.9, large). Higher values in area, range and amplitude parameters were observed in the high difficulty pyramid compared with low difficulty pyramids. In addition, higher values were observed in the anteroposterior amplitude of the CoP excursion versus the mediolateral amplitude in the three pyramids analysed. The differences observed in the parameters that described the CoP excursion were not as clear as the parameters which described the inter-trial variability. Significant differences were found between low and high difficulty pyramids in CoP area ($Z \leq -2.14$, $P < 0.05$, effect size ≤ -0.6, large) and CoP range ($Z = -2.49$, $P < 0.05$, effect size = -0.8, large), although the latter was only reported when the back pyramid was compared with the handstand pyramid. These differences indicated a greater inter-trial variability in the high difficulty pyramid compared with those of low difficulty. For the rest of inter-trial variability parameters, no differences were found between pyramids with different difficulty ($Z \geq -0.98$, $P > 0.05$, effect size ≥ -0.3, moderate).

[Table 1]

The results showed a large to nearly perfect correlation between most of the parameters that described the CoP excursion and the performance regardless of the degree of difficulty of the pyramid (Figures 2-4). This association indicated that a higher score in the execution of the pyramid was associated with a lower CoP excursion. Although correlation between CoP excursion and performance in all the pyramids was observed, the magnitude of the association changed depending on the degree of difficulty of the pyramid. The high difficulty pyramid showed higher correlation coefficients ($\rho \geq -0.801$, very large) than the low difficulty pyramids ($\rho \geq -0.303$, moderate).

[Figure 2]

[Figure 3]

[Figure 4]

Statistically significant correlations were found between performance and all the inter-trial variability measures, but only in the high difficulty pyramid ($\rho \geq -0.522$, large, see Figure 4). The relationship showed that a lower variability between trials was associated with a higher score awarded by the judges. In contrast, in the low difficulty pyramids no statistically significant correlations between scores and the inter-trial variability parameters were found ($\rho \leq -0.444$, moderate), except in the area covered by the CoP in the Front pyramid ($\rho = -0.691$, large, see Figure 3).

Discussion and Implications

The main findings of this study showed the CoP outcomes and their inter-trial variability as important factors associated with the pyramid performance. A better performance in the pyramids (judges' highest scores) was associated with improved balance (i.e. shorter displacements of the CoP) regardless of the difficulty level of the pyramid executed. Moreover, it was found that the more difficult pyramid showed greater variability across trials for the area covered by the CoP, compared to the simplest pyramids (Back and Front pyramids). The pairs that showed the greatest variability in the movements of the CoP between trials obtained worse scores, but only in the most difficult pyramid.

The results of this study showed that the CoP was sensitive to the increase in the pyramid difficulty when the pyramids were performed by experienced acrobatic gymnasts. These findings were consistent with previous studies showing that the CoP displacement increases with the difficulty of the task (Bisson, Chopra, Azzi, Morgan, & Bilodeau, 2010; Lubetzky, Price, Ciol, Kelly, & McCoy, 2015; Caballero et al., 2016; Nandi et al., 2018). The balance control in the pyramids was weaker in the anteroposterior direction than in the mediolateral direction. The amplitude of the CoP excursion was higher in the anteroposterior direction than the mediolateral direction in all the pyramids and increased with respect to difficulty. This higher excursion in anteroposterior direction with respect to the orthogonal direction could be related to foot placement. Although, one might expect that a posture where one foot is slightly in front on the other could be an advantage to control the pyramid balance, this is not necessarily the case. Previous studies have observed that the anteroposterior sway does not decrease when the feet are extended in an anteroposterior direction (Kirby, Price, & MacLeod, 1987). In the present study, the foot placement was not controlled to ensure the specific stabilization strategies of each gymnast were not limited to maintain balance. Gibbons, Amazeen and Likens (2019) observed greater stability when the participants were allowed a self-selected foot placement compared to an imposed placement. This advantage emerged primarily from the change in foot position and not stance width. Further studies which investigate the relationship of stance width and foot angle with pyramid performance are needed to determine the instructions that should be given on foot placement.

The effect of the task difficulty was more evident in the Back pyramid than in the Front pyramid although the Federation International of Gymnastics (2016) scores the same value to both pyramids suggesting that the Front pyramid could be classified as a more difficult skill than the Back pyramid. In the Back pyramid, the top gymnast's feet have an extra support on the base gymnast's clavicles, while in the Front pyramid, the support of the top gymnast's feet is provided exclusively on the base gymnast's hands (Figure 1). This finding could suggest that the monitoring of the CoP excursion could be a useful tool to evaluate the effect of changes in the technique pyramids execution, since the CoP excursion was sensitive to small changes in the grip technique used by the base. Although further studies analysing the influence of techniques changes in pyramids execution on balance ability are necessary.

The correlational part of this study showed that there was a clear relationship between the CoP excursion and performance in the pyramids. For all the pyramids studied regardless of the level of difficulty, a lower CoP excursion was related to a higher judge score (Figures 2-4). These results suggest that the pyramid instability perceived by the judges could be quantified by the CoP excursion, although this is not a direct measure of the postural sway. In this sense, postural sway relates more to the motion of the centre of mass, however the estimation of the CoP excursion is simpler than the determination of centre of mass excursion, so CoP excursion could be a more practical measure of instability in a training environment. These results are consistent with those reported by Floría et al. (2015) who proposed the record of CoP excursion as a useful tool to assess the acrobatic pyramid performance. In the present study, several balance measures have been used to determine which of them explains the performance in pyramids to a greater extent. The balance measure with the highest correlation coefficient changed in each pyramid analysed. In the Back pyramid the highest correlation coefficient was reached by the CoP area, while in the Front pyramid it was the anteroposterior amplitude and in the Handstand pyramid it was the range. This discrepancy in the results complicates the choice of which balance measure could be used by coaches and gymnasts to assess the performance in acrobatic pyramids. This problem was already suggested by Ruhe, Fejer and Walker (2010) who indicated that to evaluate balance it is necessary to include parameters that describe the distance, time-distance relation and direction of the CoP excursion. Anyway, more studies are necessary to determine which balance measure provides more useful information about pyramid performance indistinctly of the performed positions.

The results showed that the correlation between CoP excursion and performance was higher in the high difficulty pyramid compared with low difficulty pyramids. These results could be caused by the greater range of scores observed in the high difficulty pyramid compared with the low difficulty pyramids. The higher requirement of the high difficulty pyramid causes the appearance of a greater number of errors observed by the judges, which are reflected in the CoP excursion. Therefore, the judges scoring system could be limited by floor and ceiling effects (Kleffelgaard, Langhammer, Sandhaug, Pripp, & Søberg, 2018), given that the score ranges from 0 to 5 points and 0.5 points is subtracted for each slight penalty detected. Consequently, the use of CoP analysis, as a tool to evaluate performance in the pyramids could be more useful as the pyramid difficulty increases.

The inter-trial variability was only sensitive to the difficulty of task when the variability of CoP surface area was compared between low and high difficulty pyramids. The rest of the parameters used to describe the inter-trial variability did not change when the difficulty of the pyramid was increased. In this sense, the relationship between the inter-trial variability and difficulty of the task did not seem clear. There are conflicting results in the literature regarding the relationship between inter-trial variability and task difficulty (Bullock, Hopkins, Martin, & Marino, 2009; Willey & Liu, 2018). Bullock et al. (2009) found an increase in run-to-run time variability when the technical difficulty of the skeleton track increased. While, Willey and Liu (2018) observed in beanbag throwing, that inter-trial outcome variability was not influenced by the distance to the target. Taken together, these results do not support a clear relationship between the inter-trial variability and task difficulty, so further studies are necessary to explore this relationship in different motor skills.

The correlation between inter-trial variability and performance was only evident in the high difficulty pyramid, with the exception in the inter-trial variability of the surface area in the Front pyramid. Higher performance in the pyramid execution was accompanied by a low inter-trial variability. The homogeneity in performance of low difficulty pyramids could determine to some extent the absence of significant correlation between inter-trial variability and score. There are studies that indicate a decrease in variability of movement patterns with concurrent improvement in performance suggesting a progress towards the 'control' stage of learning (Chow, Davids, Button, & Koh, 2008). However, this study did not obtain measures on movement patterns, but rather outcome measures and their variability between trials. Previous studies have confirmed the relationship between higher sports performance and lower variability between trials in variables associated directly with the performance or task outcome (Anderson, Breed, Spittle, & Larkin, 2018; Bullock et al., 2009; Malcata & Hopkins, 2014). Estimates of the variability in competitive performance of each athlete provide the thresholds for assessing performance changes (Bullock et al., 2009; Malcata & Hopkins, 2014). This variability from competition to competition (inter-trial) has been extensively studied with respect to changes in final performance measures, e.g. time, distance, subjective scores (Malcata & Hopkins, 2014). In acrobatic gymnastics, the maintenance of static pyramids is a key factor on determination of the scores and, therefore, in the final performance of the competition exercise. In the present study, CoP excursion has been shown as an indirect measure of balance closely associated with pyramid scores. In this sense and according to our results, coaches and gymnasts could use lower CoP excursion in a pyramid and its lower inter-trial variability during practise to select the pyramids with the highest probability of success in competition exercises.

Although there was a correlation between inter-trial variability and pyramid performance, these correlation coefficients were lower than those reported for the relationship between outcome and pyramid performance. Furthermore, the magnitude of the effect of the difficulty was greater in the outcome measures than inter-trial variability measures. These results suggest that outcome parameters may explain the pyramid performance in acrobatic gymnasts to a greater extent than inter-trial variability, and therefore provide greater utility as a tool for the control of training and its performance of the outcome measures versus inter-trial variability measure.

It is recognised that this study has certain limitations. The present study analysed the CoP excursion of the entire pyramid, without differentiating top and base gymnast. An individual analysis of gymnasts could provide a deeper knowledge about the top and base roles to achieve the pyramid balance. Nevertheless, acrobatic gymnastics is a team sport since the scores given by the judges are applied to the complete pyramid without differentiating the base and top execution separately according to the code of points (Federation Internationale de Gymnastique, 2017). For this reason, this study aimed to evaluate the relationship between performance and pyramid balance understanding this as a single system formed by a base and a top.

Conclusions

The specific balance manifested in the pyramids analysed in this study has had limited attention in the scientific literature to date, despite its importance to performance in this sport, or its importance in understanding of the mechanisms of maintaining static positions composed by more than one person. This study has demonstrated a clear effect of the degree of difficulty of the pyramids on the CoP excursion. The effect of the difficulty on its inter-trial variability was less evident because only one of the variables analysed changed when the difficulty of the pyramid increased, however, the CoP outcomes showed a stronger relationship with the pyramid performance than its inter-trial variability. Consequently, these results suggest that CoP excursion is more related to the difficulty and performance of acrobatic pyramids than its inter-trial variability. The findings may have significant practical implications for acrobatic gymnastic training since evaluation of instability provided by the CoP excursion could provide quick and accurate information about balance and performance of acrobatic pyramids, allowing coaches to select pyramids with less instability and, consequently, with better scores.

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References

Anderson, D., Breed, R., Spittle, M., & Larkin, P. (2018). Factors Affecting Set Shot Goal-kicking Performance in the Australian Football League. *Perceptual and Motor Skills*, *125*(4), 817–833. https://doi.org/10.1177/0031512518781265

Baida, S. R., Gore, S. J., Franklyn-Miller, A. D., & Moran, K. A. (2018). Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review. *Scandinavian Journal of Medicine and Science in Sports*, *28*(4), 1320–1338. https://doi.org/10.1111/sms.13036

Bisson, E. J., Chopra, S., Azzi, E., Morgan, A., & Bilodeau, M. (2010). Acute effects of fatigue of the plantarflexor muscles on different postural tasks. *Gait & Posture*, *32*(4), 482–486. https://doi.org/10.1016/j.gaitpost.2010.07.006

Blenkinsop, G. M., Pain, M. T. G., & Hiley, M. J. (2016). Evaluating feedback time delay during perturbed and unperturbed balance in handstand. *Human Movement Science*, *48*, 112–120. https://doi.org/10.1016/j.humov.2016.04.011

Bradshaw, E. J., Maulder, P. S., & Keogh, J. W. L. (2007). Biological movement variability during the sprint start: Performance enhancement or hindrance? *Sports Biomechanics*, *6*(3), 246–260. https://doi.org/10.1080/14763140701489660

Bullock, N., Hopkins, W. G., Martin, D. T., & Marino, F. E. (2009). Characteristics of performance in skeleton World Cup races. *Journal of Sports Sciences*, *27*(4), 367-372. https://doi.org/10.1080/02640410802613425

Busquets, A., Marina, M., Davids, K., & Angulo-Barroso, R. (2016). Differing roles of functional movement variability as experience increases in gymnastics. *Journal of Sports Science and Medicine*, *15*(2), 268–276.

Caballero, C., Barbado, D., Davids, K., & Moreno, F. J. (2016). Variations in task constraints shape emergent performance outcomes and complexity levels in balancing. *Experimental Brain Research*, *234*(6), 1611–1622. https://doi.org/10.1007/s00221-016-4563-2

Chow, J. Y., Davids, K., Button, C., & Koh, M. (2008). Coordination changes in a discrete multi-articular action as a function of practice. *Acta Psychologica*, *127*(1), 163-176. https://doi.org/10.1016/j.actpsy.2007.04.002

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences*. New York, NY: Academic Press.

Davids, K., Glazier, P., Araújo, D., & Bartlett, R. (2003). Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. *Sports Medicine*, *33*(4), 245–260. https://doi.org/10.2165/00007256-200333040-00001

Federation Internationale de Gymnastique. (2016). *Code of points acrobatic gymnastics. Tables of difficulty 2017-2020*. (Federation Internationale de Gymnastique, Ed.). Laussane.

Federation Internationale de Gymnastique. (2017). *2017 – 2020 Code of Points Acrobatic Gymnastics*. (Federation Internationale de Gymnastique, Ed.). Laussane.

Floría, P., Gómez-Landero, L. A., & Harrison, A. J. (2015). Centre of pressure correlates with pyramid performance in acrobatic gymnastics. *Sports Biomechanics, 14*(4), 424–434. https://doi.org/10.1080/14763141.2015.1084032

Gibbons, C. T., Amazeen, P. G., & Likens, A. D. (2019). Effects of foot placement on postural sway in the anteroposterior and mediolateral directions. *Motor Control, 23*(2), 149–170. https://doi.org/10.1123/mc.2017-0074

Glazier, P. S., Wheat, J. S., Pease, D. L., & Bartlett, R. M. (2006). The interface of biomechanics and motor control. Dynamic systems theory and the functional role of movement variability. In K. Davids, S. Bennett, & K. Newell (Eds.), *Movement System Variability* (pp. 59–69). Champaign, IL: Human Kinetics.

Hiley, M. J., Zuevsky, V. V., & Yeadon, M. R. (2013). Is skilled technique characterized by high or low variability? An analysis of high bar giant circles. *Human Movement Science, 32*(1), 171–180. https://doi.org/10.1016/j.humov.2012.11.007

Hopkins, W. G. (2006). A scale of magnitudes for effect statistics. Retrieved July 18, 2019, from https://www.sportsci.org/resource/stats/effectmag.html

Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Medicine, 41*(3). https://doi.org/10.2165/11538560-000000000-00000

Iino, Y., Yoshioka, S., & Fukashiro, S. (2017). Uncontrolled manifold analysis of joint angle variability during table tennis forehand. *Human Movement Science*, *56*, 98–108. https://doi.org/10.1016/j.humov.2017.10.021

Jeter, P. E., Wang, J., Gu, J., Barry, M. P., Roach, C., Corson, M., Yang, L., & Dagnelie, G. (2015). Intra-session test-retest reliability of magnitude and structure of center of pressure from the Nintendo Wii Balance Board^{TM} for a visually impaired and normally sighted population. *Gait and Posture*, *41*, 482-487. https://doi.org/10.1016/j.gaitpost.2014.11.012

Kirby, R.L., Price, N.A., & MacLeod, D.A. (1987). The influence of foot position on standing balance. *Journal of Biomechanics, 20*(4), 423–427. https://doi.org/10.1016/0021-9290(87)90049-2

Kleffelgaard, I., Langhammer, B., Sandhaug, M., Pripp, A. H., & Søberg, H. L. (2018). Measurement properties of the modified and total Balance Error Scoring System–the BESS, in a healthy adult sample. *European Journal of Physiotherapy*, *20*(1), 25–31. https://doi.org/10.1080/21679169.2017.1352020

Ko, J. H., Han, D. W., & Newell, K. M. (2018). Skill level changes the coordination and variability of standing posture and movement in a pistol-aiming task. *Journal of Sports Sciences*, *36*(7), 809–816. https://doi.org/10.1080/02640414.2017.1343490

Kochanowicz, A., Niespodziński, B., Marina, M., Mieszkowski, J., Biskup, L., & Kochanowicz, K. (2018). Relationship between postural control and muscle activity during a handstand in young and adult gymnasts. *Human Movement Science, 58*, 195–204. https://doi.org/10.1016/j.humov.2018.02.007

Lenetsky, S., Brughelli, M., Nates, R. J., Cross, M. R., & Lormier, A. V. (2018). Variability and reliability of punching impact kinetics in untrained participants and experienced boxers. *Journal of Strength and Conditioning Research, 32*(7), 1838–1842. https://doi.org/10.1519/JSC.0000000000002352

Lubetzky, A. V., Price, R., Ciol, M. A., Kelly, V. E., & McCoy, S. W. (2015). Relationship of multiscale entropy to task difficulty and sway velocity in healthy young adults. *Somatosensory & Motor Research*, *32*(4), 211–218. https://doi.org/10.3109/08990220.2015.1074565

Malcata, R. M., & Hopkins, W. G. (2014). Variability of Competitive Performance of Elite Athletes: A Systematic Review. *Sports Medicine*, *44*(12), 1763–1774. https://doi.org/10.1007/s40279-014-0239-x

Miletic, D., Sekulic, D., & Wolf-Cvitak, J. (2004). The leaping performance of 7-year-old novice rhythmic gymnasts is highly influenced by the condition of their motor abilities. *Kinesiology*, *36*, 35–43.

Nandi, T., Lamoth, C. J. C., van Keeken, H. G., Bakker, L. B. M., Kok, I., Salem, G. J., Fisher, B. E., & Hortobágyi, T. (2018). In standing, corticospinal excitability is proportional to COP velocity whereas M1 excitability is participant-specific. *Frontiers in Human Neuroscience*, *12*, 303. https://doi.org/10.3389/fnhum.2018.00303

Negahban, H., Aryan, N., Mazaheri, M., Norasteh, A. A., & Sanjari, M. A. (2013). Effect of expertise in shooting and Taekwondo on bipedal and unipedal postural control isolated or concurrent with a reaction-time task. *Gait & Posture*, *38*(2), 226–230. https://doi.org/10.1016/j.gaitpost.2012.11.016

Omorczyk, J., Bujas, P., Puszczałowska-Lizis, E., & Biskup, L. (2018). Balance in handstand and postural stability in standing position in athletes practicing gymnastics. *Acta of Bioengineering and Biomechanics Original Paper*, *20*(2), 139–147. https://doi.org/10.5277/ABB-01110-2018-02

Opala-Berdzik, A., Głowacka, M., Wilusz, K., Kołacz, P., Szydło, K., & Juras, G. (2018). Quiet standing postural sway of 10-to 13-year-old, national-level, female acrobatic gymnasts. *Acta of Bioengineering and Biomechanics*, *20*(2), 117–123. https://doi.org/10.5277/ABB-01060-2017-02

Pajek, M. B., Cuk, I., Pajek, J., Kovac, M., & Leskošek, B. (2013). Is the quality of judging in women artistic gymnastics equivalent at major competitions of different levels? *Journal of Human Kinetics*, *37*(1), 173–181. https://doi.org/10.2478/hukin-2013-0038

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, *12*(2), 69–92. https://doi.org/10.1080/14763141.2012.738700

Rohleder, J., & Vogt, T. (2018). Performance control in handstands: challenging entrenched coaching strategies for young gymnasts. *International Journal of Performance Analysis in Sport*, *18*(1), 17–31. https://doi.org/10.1080/24748668.2018.1440459

Rosenthal, R. (1994). Parametric measures of effect size. In H. Cooper & L. V. Hedges (Eds.), *The handbook of research synthesis.* (pp. 231-244). New York: Russell Sage Foundation.

Ruhe, A., Fejer, R., & Walker, B. (2010). The test–retest reliability of centre of pressure measures in bipedal static task conditions – A systematic review of the literature. *Gait & Posture*, *32*(4), 436–445. https://doi.org/10.1016/J.GAITPOST.2010.09.012

Serrien, B., Goossens, M., & Baeyens, J. P. (2018). Proximal-to-Distal Sequencing and

Coordination Variability in the Volleyball Spike of Elite Youth Players: Effects of Gender and Growth. *Journal of Motor Learning and Development*, *6*(2), 250–266. https://doi.org/10.1123/jmld.2017-0049

Shigaki, L., Rabello, L. M., Camargo, M. Z., Batista, V., Santos, C., Wilson, A., Gil, O., Rogério De Oliveira, M., Alexandre Da, R., Junior, S., De Souza, C., Macedo, G., & Guerino Macedo, C. D. S. (2013). Comparative analysis of one-foot balance in rhythmic gymnastics athletes. *Revista Brasileira de Medicina Do Esporte, 19*(2), 104–107.

Sobera, M., Siedlecka, B., Piestrak, P., Sojka-Krawiec, K., & Graczykowska, B. (2007). Maintaning body balance in extreme positions. *Biology of Sport*, *24*(1), 81–88.

Steinberg, N., Waddington, G., Adams, R., Karin, J., & Tirosh, O. (2018). Should ballet dancers vary postures and underfoot surfaces when practicing postural balance? *Motor Control*, *22*(1), 45–66. https://doi.org/10.1123/mc.2016-0076

Wilson, C., Simpson, S., Van Emmerik, R., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, *7*(1), 2–9. https://doi.org/10.1080/14763140701682983

Willey, C. R., & Liu, Z. (2018). Long-term motor learning: Effects of varied and specific practice. *Vision Research*, *152*, 10–16. https://doi.org/10.1016/j.visres.2017.03.012

Table 1. Descriptive statistics (medians and 95% confidence limits) for the scores and balance parameters studied in each evaluated pyramid. Comparative statistic (p value, effect size) between low difficulty and high difficulty pyramids.

	Variable	Low Difficulty						High Difficulty	
		Back Pyramid (n=12)		Effect Size Back-Handstand (p)	Front pyramid (n=13)		Effect Size Front-Handstand (p)	Handstand pyramid (n=24)	
	Pyramid score[c]	4.1	(3.9 - 4.2)	-0.9 (0.003)	4.1	(3.8 - 4.2)	-0.9 (0.001)	2.8[ab]	(2.1 - 3.6)
CoP outcomes	CoP area (m^2)	0.0010	(0.0008 - 0.0014)	-0.9 (0.003)	0.0014	(0.0012 - 0.0019)	-0.9 (0.001)	0.0072[ab]	(0.0034 - 0.0113)
	CoP range (m)	0.06	(0.05 - 0.07)	-0.9 (0.003)	0.07	(0.06 - 0.09)	-0.9 (0.001)	0.18[ab]	(0.12 - 0.22)
	CoP $amplitude_{ml}$ (m)	0.03	(0.03 - 0.04)	-0.9 (0.003)	0.04	(0.03 - 0.05)	-0.9 (0.001)	0.09[ab]	(0.06 - 0.11)
	CoP $amplitude_{ap}$ (m)	0.05	(0.04 - 0.06)	-0.9 (0.003)	0.06	(0.05 - 0.07)	-0.9 (0.001)	0.14[ab]	(0.10 - 0.16)
Inter-trial variability	CoP area (m^2)	0.0001	(0.0000 - 0.0003)	-0.8 (0.007)	0.0003	(0.0001 - 0.0005)	-0.6 (0.033)	0.0017[ab]	(0.0004 - 0.0029)
	CoP range (m)	0.01	(0.01 - 0.02)	-0.8 (0.013)	0.02	(0.01 - 0.03)	-0.1 (0.600)	0.02[a]	(0.01 - 0.04)
	CoP $amplitude_{ml}$ (m)	0.01	(0.00 - 0.03)	-0.3 (0.328)	0.01	(0.01 - 0.02)	-0.2 (0.507)	0.01	(0.01 - 0.02)
	CoP $amplitude_{ap}$ (m)	0.01	(0.00 - 0.02)	-0.3 (0.374)	0.01	(0.01 - 0.03)	-0.2 (0.402)	0.02	(0.01 - 0.03)

CoP: centre of pressure. [a]Differences between Back-Handstand pyramid, $p < 0.05$. [b]Differences between Front-Handstand pyramid, $p < 0.05$. [c]Scoring range from 0 to 5.

Figures caption

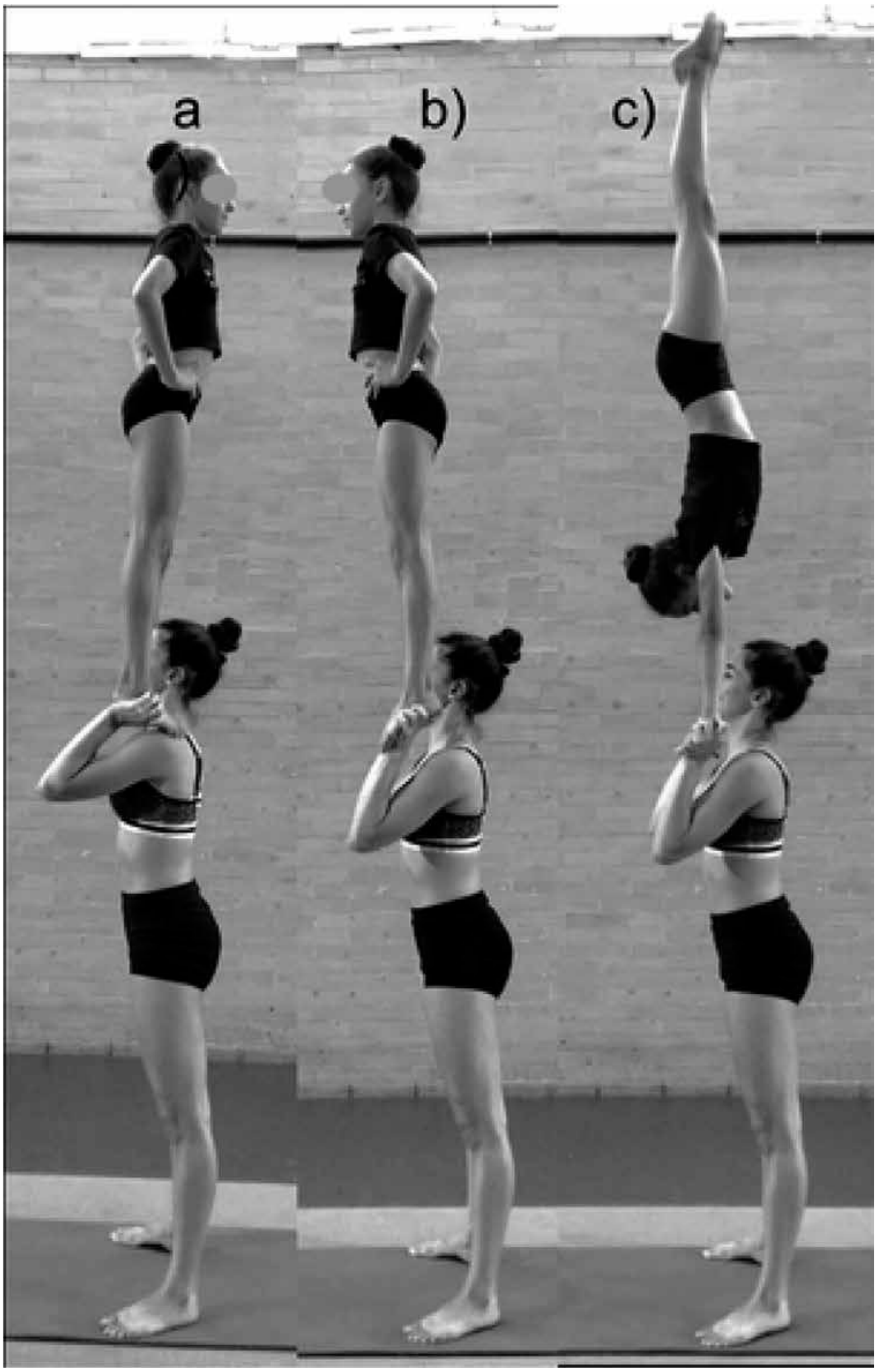

Figure 1. Images of the stand back on bent elbows pyramid (a), stand front on bent elbows pyramid (b) and handstand on bent elbows pyramid (c).

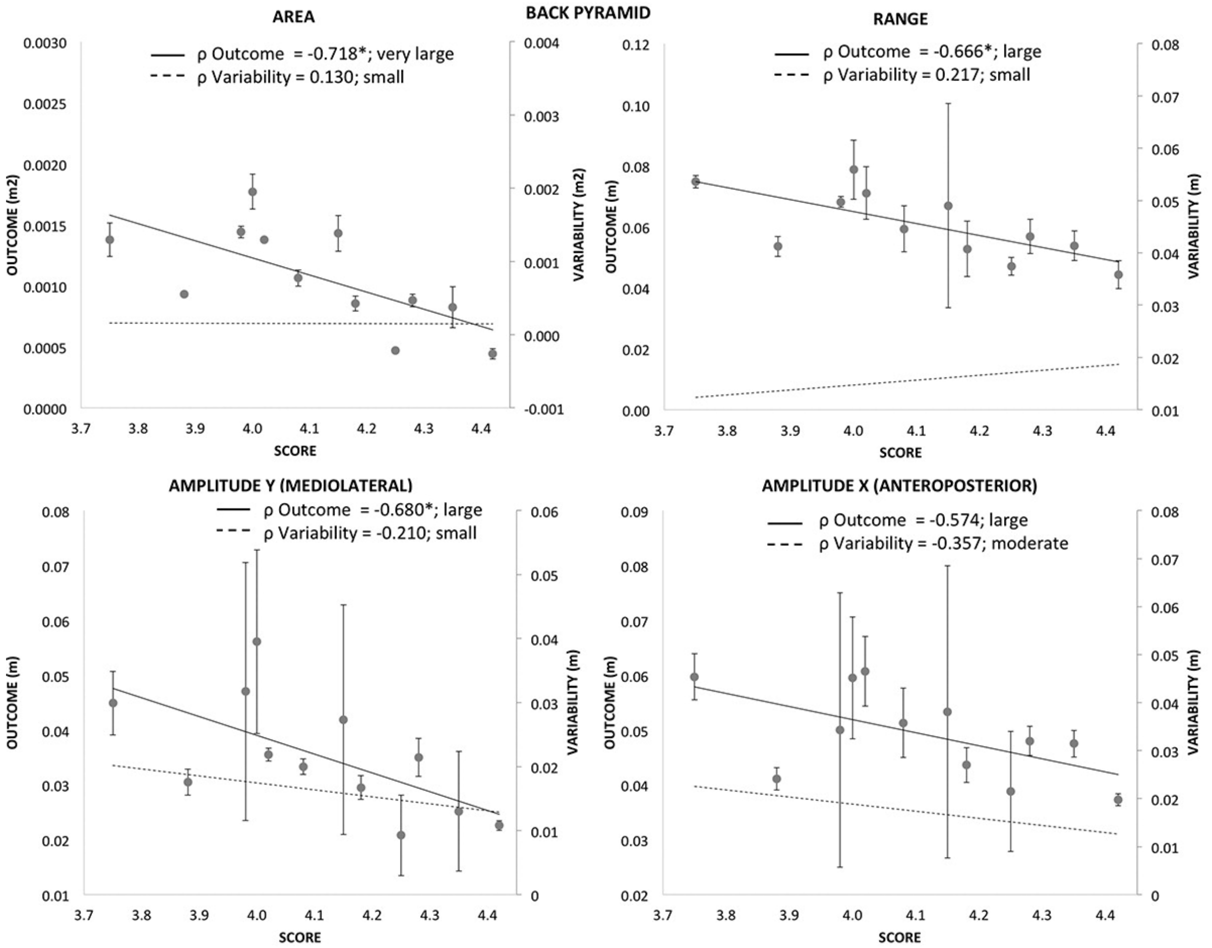

Figure 2. Spearman's coefficients correlations (ρ) between Back pyramid score of each pair, with the median value of balance parameters (ρ outcome), and with the median absolute deviation (MAD) of the 5 trials (ρ variability). The continuous lines represent the regression line of the outcome values (axis on the left). The dashed lines represent the regression line of the variability values (axis on the right). The whiskers represent the MAD. * Significant Correlation $p<0.05$. ** Significant Correlation $p<0.01$.

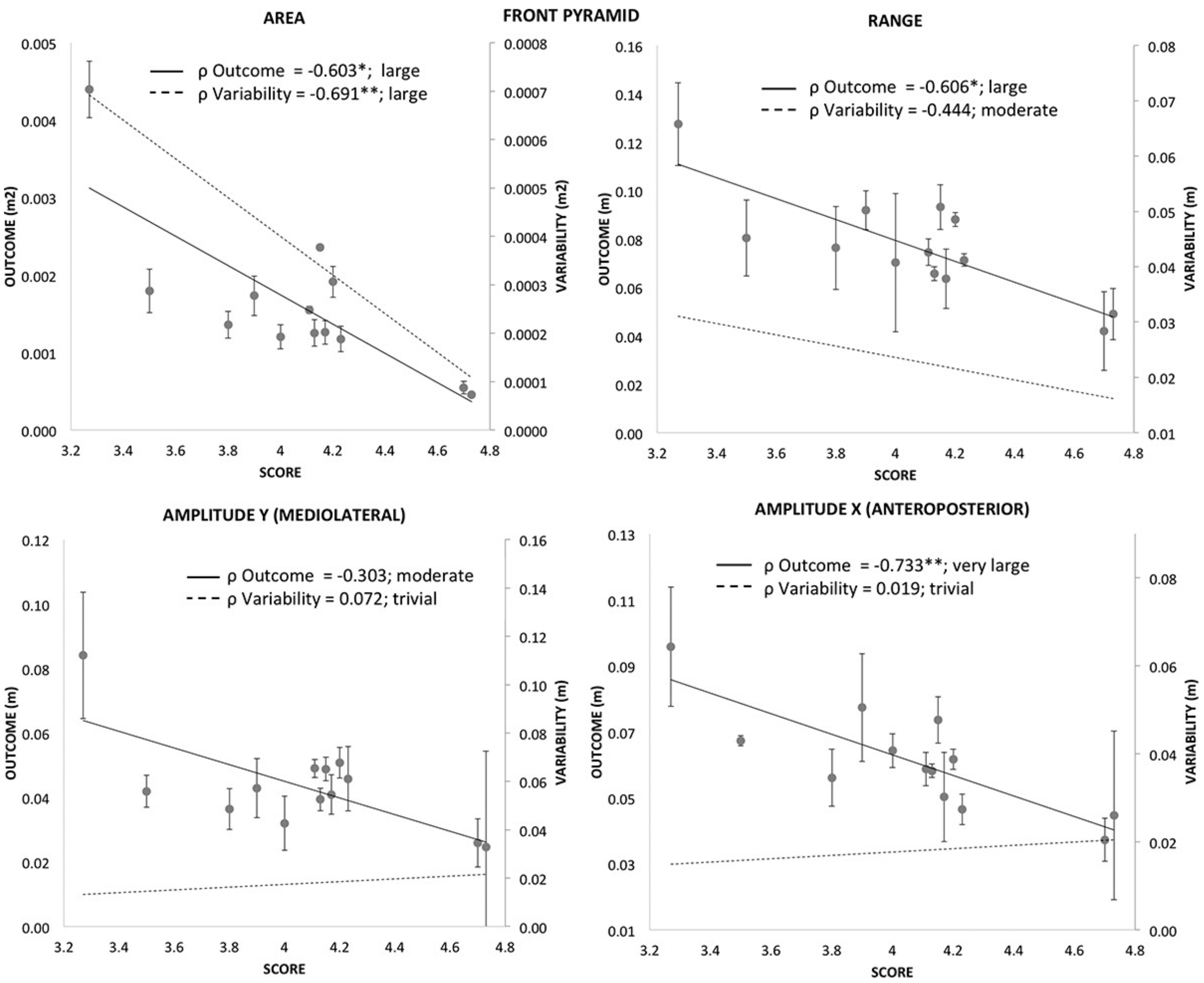

Figure 3. Spearman's coefficients correlations (ρ) between Front pyramid score of each pair, with the median value of balance parameters (ρ outcome), and with the median absolute deviation (MAD) of the 5 trials (ρ variability). The continuous lines represent the regression line of the outcome values (axis on the left). The dashed lines represent the regression line of the variability values (axis on the right). The whiskers represent the MAD. * Significant Correlation p<0.05. ** Significant Correlation p<0.01.

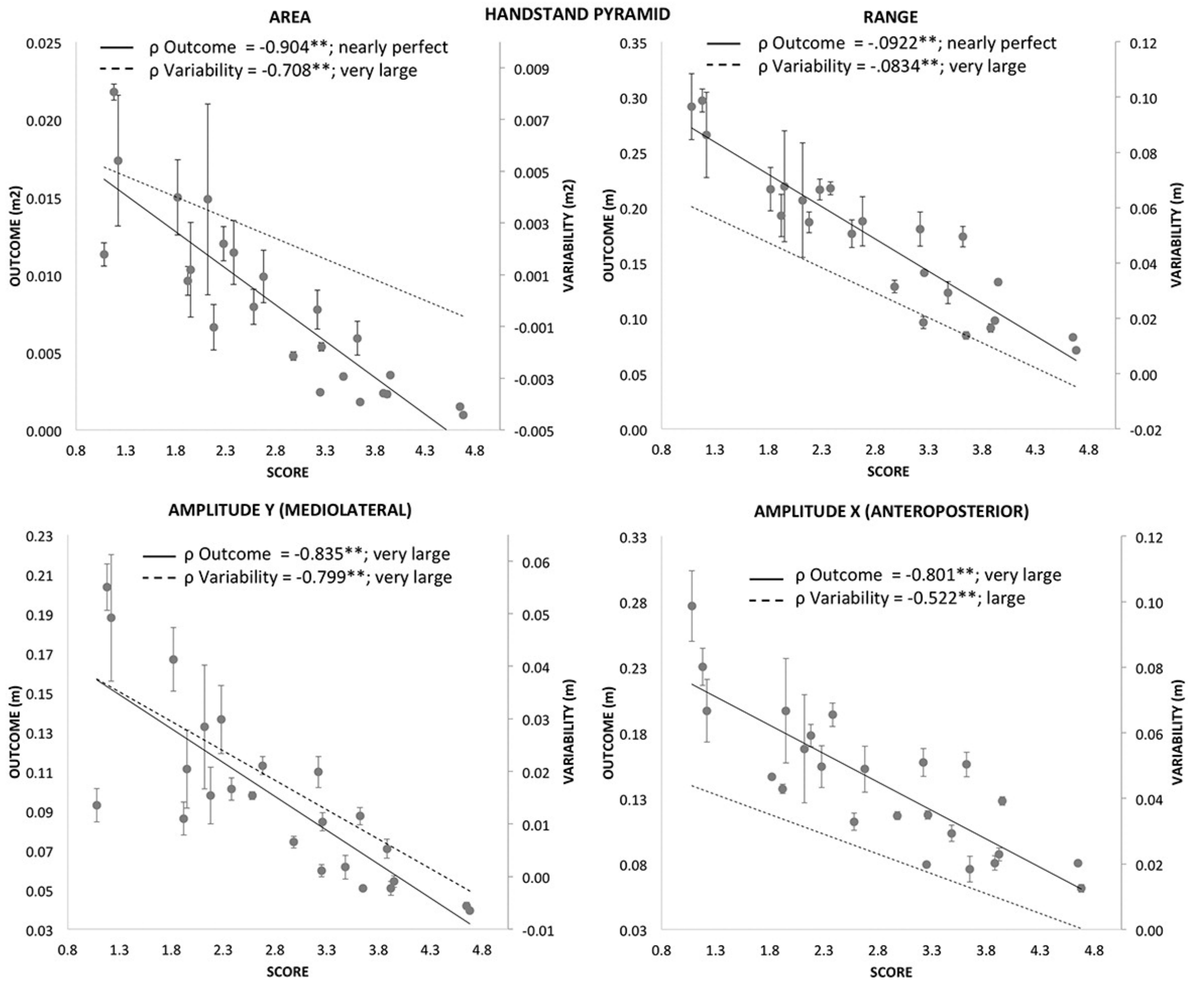

Figure 4. Spearman's coefficients correlations (ρ) between Handstand pyramid score of each pair, with the median value of balance parameters (ρ outcome), and with the median absolute deviation (MAD) of the 5 trials (ρ variability). The continuous lines represent the regression line of the outcome values (axis on the left). The dashed lines represent the regression line of the variability values (axis on the right). The whiskers represent the MAD. * Significant Correlation p<0.05. ** Significant Correlation p<0.01.